RECOVERY CHARACTERISTICS OF HYDROGEN SPARK GAP SWITCHES

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Abstract

Many applications and laboratory-scale experiments make use of gas spark-gap switches because of their high power handling capability and simplicity. A simultaneous requirement of high repetition-rate, however, has traditionally excluded their use when repetition-rates above a few hundred hertz are necessary. The use of hydrogen, as well as operating a triggered gas switch in an undervolted mode, can result in recovery times as short as 100 μs.

As part of a program to develop high repetition-rate switches for recirculating accelerators, a series of experiments have been performed to determine the recovery characteristics of high-pressure hydrogen switches under a variety of pulse conditions. The recovery curve for hydrogen obtained at low discharge energies and small gap spacings was found to be reasonably predictive of the recovery one could expect for energies up to 12 kJ, for currents to 170 kA, for voltages to 500 kV, and for gap spacings to 3 cm. Burst-mode measurements indicate that jitter can be limited to a few nanoseconds and that multiple pulses in a burst do not significantly degrade recovery. Details of these experiments will be presented.

Introduction

High pressure spark gap switches merit broad application due to their range of triggerability, large operating voltages and dI/dt characteristics. Spark gaps are conceptually simple and easy to fabricate so that they are often a very cost effective solution to a particular switching problem. Although they are very suitable for single-shot and relatively low average power applications, their use in high repetition-rate, high average power situations is hampered by their limited recovery and lifetime [1,2]. The present experimental work will address one aspect of the problem, namely spark gap recovery.

Applications such as compact, repetitive, recirculating accelerators and high power microwave sources for directed energy applications require repetition rates beyond the capability of conventional spark gap switches. Figure 1 compares recovery data for commonly used gases such as air, nitrogen, argon and SF_6 with that of hydrogen for a standard center-pin trigatron switch configuration. Without resorting to gas flow, order-of-magnitude improvement in recovery time can typically be achieved using hydrogen gas. An additional order-of-magnitude improvement can be obtained by operating the switch in a highly undervolted state, i.e. at less than 50% of its static self-break voltage. Since these switches normally operate at very high pressures with relatively small gap spacings, and require no gas flow, an additional advantage in overall system size can be realized. Unfortunately, as the operating voltage of such a switch is raised, building a suitable triggering system becomes a major issue.

Previous work has demonstrated two-pulse recovery at relatively low voltages, but at high currents and energies [3]. Recovery times of 100 μs were achieved at 50 kV, 12.5 kJ, 170 kA, with 10 μs pulses. The focus of our recent work has been to demonstrate that the same recovery characteristics can be achieved at much higher voltages and for multiple pulses in a burst.

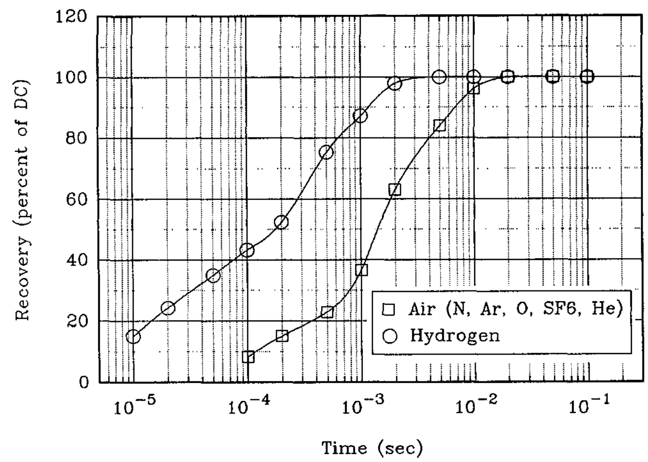

Figure 1. Recovery curves for gases at 200 psi, 2.5 mm gap, and 9 J energy transfer.

Experimental Setup

The investigation of hydrogen switch recovery at high voltages for multiple pulses in a burst was made possible by the construction of the five-pulse system shown in Figure 2. The Pulsed Power Facility (50 kVDC, 4A) was used to charge the five 0.7 μF capacitors to 45 kV. Each of the capacitors is connected to the primary lug of an air-core, dual-resonant, high-voltage transformer with an appropriately valued tuning inductor. The transformer charges a 5 nF secondary capacitor bank to 500 kV through another tuning inductor in approximately 11.5 μs. Since the hydrogen switches of the primary are connected in common to the input of the transformer, each must recover before the next one fires, with the exception of the fifth switch. The five switches are triggered sequentially at repetition-rates of up to 10 kHz by five single-shot 100 kV trigger generators. Maximum energy transfer between the primary and secondary of the circuit is ensured by careful adjustment of the tuning inductors so that the proper resonance conditions are met. For each pulse in the burst, the secondary capacitor bank is discharged at the maximum of the dual-resonant waveform through a 9-Ω resistive load by a single, fast-recovery hydrogen switch. The geometric inductance of the high-current discharge path is approximately 1.3 μH. The entire secondary circuit was initially immersed in deionized water and tested to 250 kV, but was later changed to transformer oil for the 500 kV tests.

The high voltage switch is a modification of a Sandia V/N switch design [4]. As shown in Figure 3, the switch is composed of a single stage with a trigger disk situated in the main gap region near the ground electrode. An additional peaking gap contained within the ground electrode enables multichannel triggering of the gap. The trigger-gap to main-gap spacing determines the V/N ratio and the required triggering voltage. The interelectrode spacing was set to 1.7 cm for an average electric field of 290 kV/cm at 500 kV. A new 1.9 cm thick housing was machined out of a solid acrylic cylinder. As can be seen, a single, rather than segmented, housing was

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14. ABSTRACT
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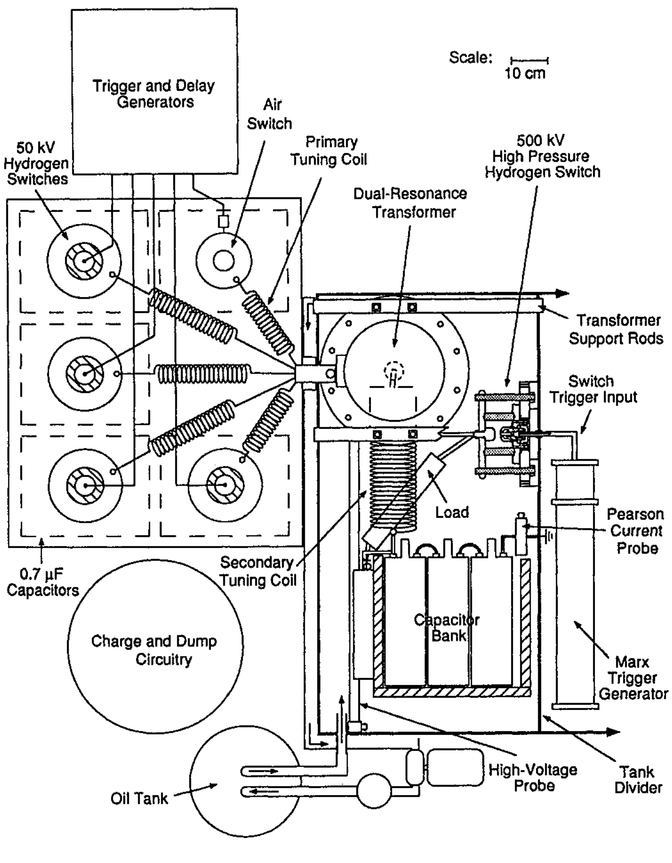


Figure 2. 5-Pulse high-voltage hydrogen switch testbed.

used with only two O-ring seals on either electrode plate. The housing was held together with high-strength TORLON 4030 polyamide plastic rods. The switch was hydrostatically pressure tested up to 1000 psig, then tested to 1000 psig in air, retorqued, and subsequently tested to 1000 psig in hydrogen.

A major concern of this effort has been the development of a compact, inexpensive device capable of triggering such a switch at 10 kHz in a 5-pulse burst. For low-jitter, low-inductance, multi-channel operation of the high voltage switch, a fast-rising pulse in excess of 100 kV is required of the trigger generator. For these experiments, a commercially available miniature Marx generator was modified to allow multi-kilohertz burst-mode operation [5]. By using hydrogen in the Marx and applying the same undervolted triggering techniques, we were able to generate a train of five 140 kV, 5-ns risetime pulses to trigger the high-voltage switch. A diagram of the entire triggering system is shown in Figure 4. Each primary gap is triggered by a single-shot 100 kV trigger generator with the interpulse separation being set by appropriate delay generators. The light output from each primary gap initiates a trigger sequence resulting in the erection of the Marx generator which then triggers the high-voltage switch. This trigger sequence is synchronized with the dual resonant voltage waveform in the secondary to allow the switching event to occur at peak voltage.

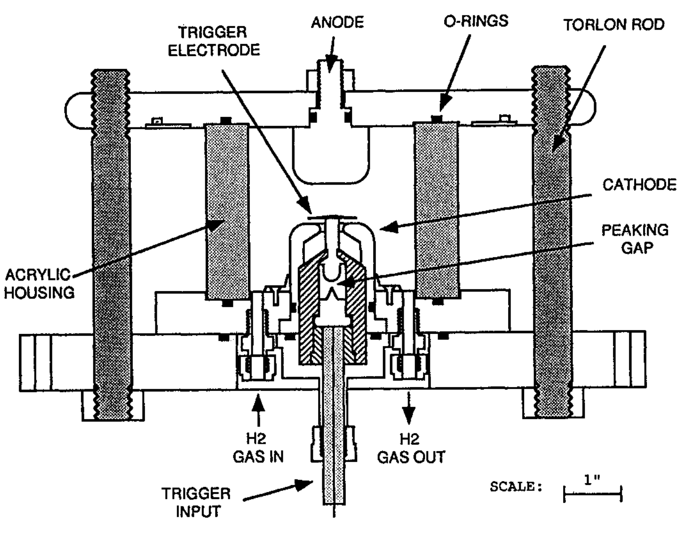


Figure 3. The 500 kV V/N hydrogen switch (pressure tested to 1000 psi).

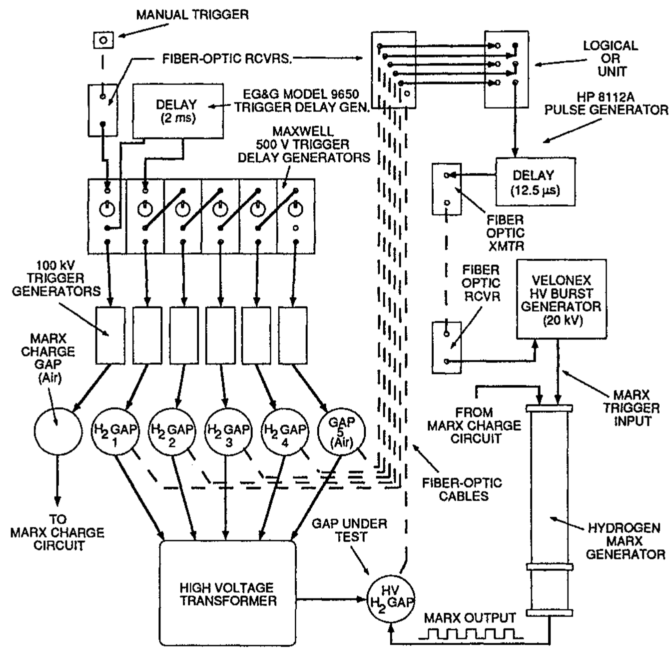


Figure 4. The 5-pulse triggering system consisting of five single-shot 100 kV trigger generators for the primary switches and the rep-rated Marx for the single high-voltage switch.

Experimental Results

The primary side of the 5-pulse system has been successfully operated in a 10 kHz, 5-pulse burst at 45 kV into a 0.375-Ω load [6]. Average power during the burst was 7 MW. A segmented insulator version of the V/N switch (V/N ratio of 5, gap spacing 1.3 cm) was used to successfully demonstrate 500 µs recovery for a burst of 5 pulses at 250 kV in 400 psig of hydrogen (at 60% of its self-break voltage), as shown in Figure 5 [7]. The rep-rate was limited only by the capability of the trigger generator. Subsequent two-pulse tests were performed with the Marx in a single-shot mode and showed 200 µs recovery time at the same pressure. This time is consistent with the recovery curves obtained with small gaps (Figure 1). In addition, tests were performed to determine jitter and delay characteristics for a 1-kHz five-pulse burst at 250 kV as a function of pressure (or percent of self-break operation). The switch delay increased as the switch was more and more undervolted, as one would expect, but did not exceed 16 ns. Jitter remained below 2 ns for each of the consecutive pulses with the exception of the first pulse when operated at the highest pressures (i.e. lowest percentage of self-break) [7].

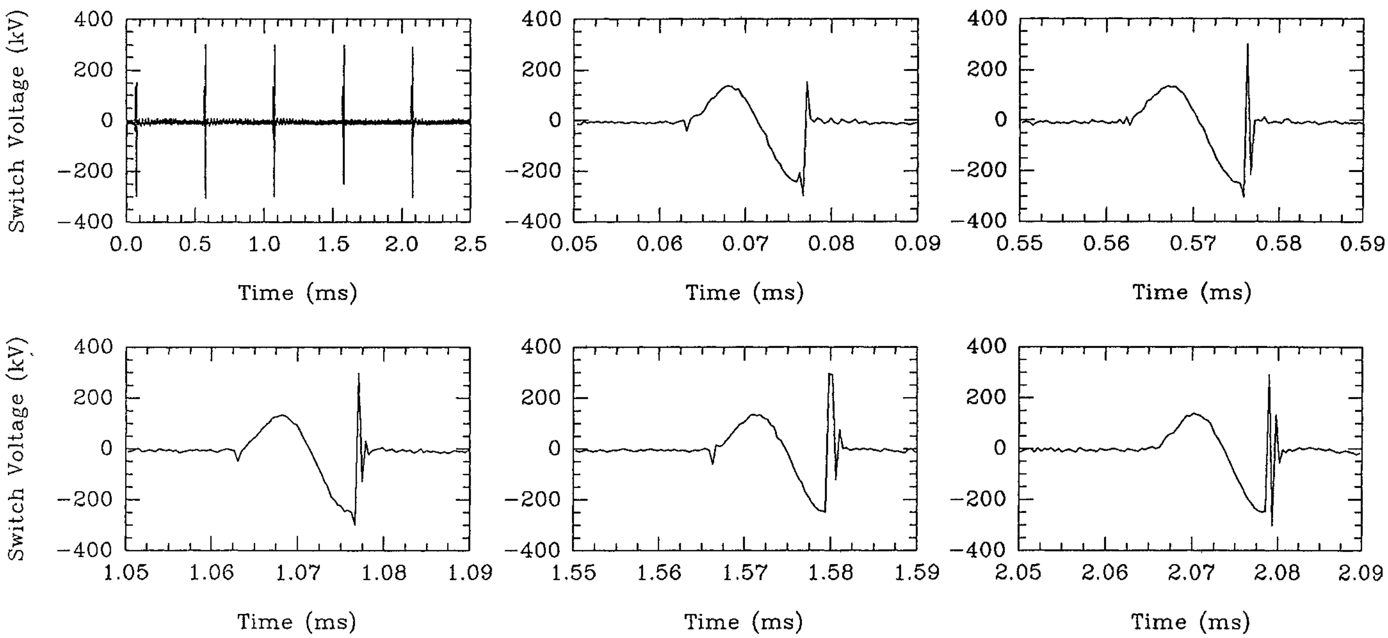


Figure 5. 5-Pulse burst at 2 kHz and 250 kV. Switch pressure was 400 psig of hydrogen, gap spacing was 1.3 cm. The first frame shows the entire pulse train, with the following frames showing each of the five successive pulses.

Recent tests have concentrated on determining the recovery characteristics of hydrogen switches at voltages up to 500 kV. With the trigger electrode removed from the gap, the self-break characteristics of the 500-kV switch were measured as a function of pressure. A plot of the results is given in Figure 6. Each data point represents a ten-shot average. The breakdown voltage is essentially linear with pressure up to about 300 psig. Beyond this point, the curve begins to roll over and any further increase in pressure does not result in as big an increase in holdoff voltage. This effect is expected at very high fields and pressures [8]. As a result, within the pressure limits of the current switch and using the present gap spacing of the single-segment pressure housing, we should expect to be limited to 1 kHz operation at 500 kV. This is due to the fact that this particular switch arrangement cannot be operated at a low percentage of self-break.

Having characterized the self-break voltage of the switch, the trigger electrode was reinstalled. As before, the V/N spark gap had to be tuned to achieve maximum self-breakdown. The stray capacitance between the trigger disk and the ground electrode, the capacitance between the trigger disk shank and the ground electrode, and the peaking gap capacitance, had to be adjusted so that the trigger disk floats at the equipotential demanded by the spark gap main electrodes. The trigger disk was moved in and out of the gap to obtain the maximum holdoff while still enabling the gap to be triggered at higher pressures. The optimum V/N trigger gap spacing was chosen to be about 1.8 mm (V/N=10). This results in a 5% reduction in voltage holdoff but still allows us to trigger the switch at fairly low percentages of self-break.

Tests were performed to verify that hydrogen recovery characteristics do in fact hold at high voltages. With the switch containing 800 psig of hydrogen, the full 500 kV was applied to the switch, with the results being shown in Figure 7. The first pulse is triggered at peak voltage and the second pulse recovers to full voltage but then breaks at some later time, indicating that the switch has barely recovered in the 1 ms time-frame. Tests at 450-kV show full recovery. Proceeding to higher pressures was not considered advisable since the switch had only been tested up to 1000 psig. These results, however, are entirely consistent with the breakdown curve of Figure 1.

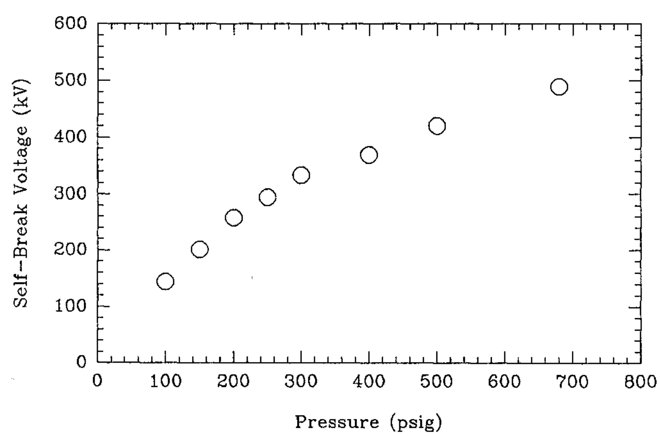
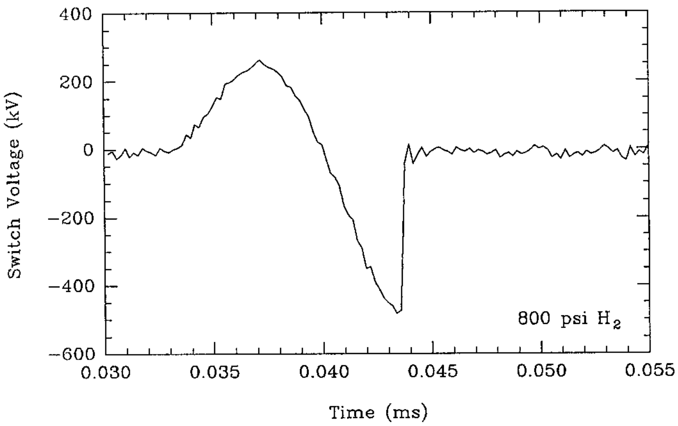


Figure 6. Self-break characteristics of the 500 kV switch vs. pressure.

Conclusions

Before this program started, the 10 kHz hydrogen switch technology had been demonstrated at low energies and in two-pulse bursts. Four major questions needed to be answered before this technology could be applied to repetitive accelerators: (1) Would the results scale to higher energies, (2) Would the results scale to higher voltages, (3) Would the results be applicable to bursts of more than two pulses, and (4) Could jitter be held to a few nanoseconds. The results to date are favorable for all four areas.

High repetition-rate switching in hydrogen has been demonstrated over a large range of parameters as shown in Table 1. Gap spacings from 1 mm to 30 mm have been tested at voltages from 20 to 500 kV at pressures up to 1000 psig with similar recovery characteristics. Five-pulse burst tests at a few



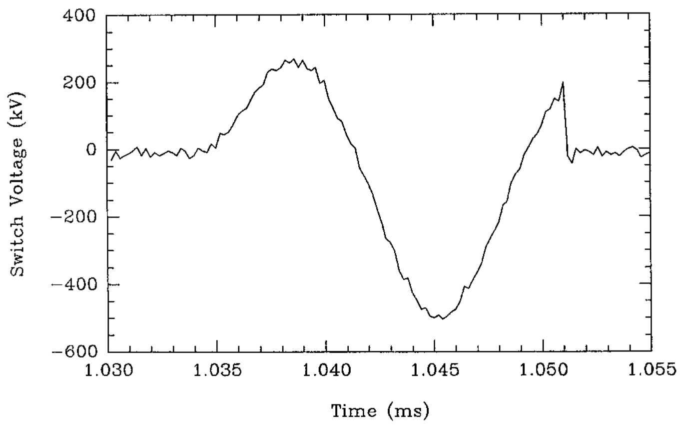


Figure 7. Two-pulse recovery of the hydrogen V/N switch at 500 kV. Gap spacing was 1.7 cm at a pressure of 800 psig.

hundred joules indicate that the recovery curves can be applied to bursts of greater length. Measurements indicate that jitter for successive pulses in a burst can be kept in the few-nanosecond range for operation down to 60% of self-break. With further improvements in the triggering system, there appears to be no reason why a 500-kV spark gap handling kilojoules of energy cannot operate in a burst-mode at 10 kHz.

Future work will concentrate on high average power operation of hydrogen spark gaps (long-bursts), and the problems associated with triggering such switches at high repetition-rates.

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Charge Voltage	Stored Energy	Capaci tance	Peak Current	Charge Transfer	Period	Pulse Length	Load	Pulses	Recovery
60 kV	200 J	116 nF	35 kA	7 mC	200 ns	200 ns	.86 Ω	2-pulse	100 μs
50 kV	12 kJ	10 μF	170 kA	1 Coul	11 μs	11 μs	0.1 Ω	2-pulse	100 μs
50 kV	12 kJ	10 μF	260 kA	8 Coul	11 μs	80 μs	.01 Ω	1-pulse	single shot
50 kV	1 kJ	.74 μF	40 kA	.1 Coul	4 μs	5 μs	.37 Ω	5-pulse	5 kHz
45 kV	750 J	.74 μF	23 kA	.3 Coul	10 μs	20 μs	.37 Ω	5-pulses	10 kHz
250 kV	200 J	6.6 nF	10 kA	5 mC	600 ns	600 ns	9 Ω	2-pulses	200 μs
250 kV	200 J	6.6 nF	10 kA	5 mC x5	600 ns	600 ns	9 Ω	5-pulses	2 kHz*
500 kV	600 J	4.8 nF	22 kA	10 mC x5	500 ns	500 ns	9 Ω	2-pulses	1 kHz*

Table 1. Summary of results from the hydrogen spark gap switch experiments.